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Permeability Testing on Dense-Graded Hot Mix Asphalt (HMA) and Gap-Graded Rubberized Hot Mix Asphalt (RHMA-G) Surfaces

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16. ABSTRACT

Falling head permeability tests were conducted on seven projects, four with dense-graded hot mix asphalt surfaces and three with gap-graded rubberized hot mix asphalt surfaces. Tests were conducted between the two wheelpaths and in the right wheelpath, and in both directions of traffic. Averaging all the test results shows that the permeability of RHMA-G is much greater than that of HMA: 2.9E-3 cm/sec versus 6.1E-4 cm/sec, respectively.

However, one of the three projects with a gap-graded rubberized hot mix asphalt surface had permeabilities not consistent with the other two. When data from that gap-graded rubberized hot mix asphalt surface was removed, the average value for the surface permeability dropped over 80 percent, to 4.2E-4 cm/sec. This average is lower than the average permeability for dense-graded hot mix asphalt, and the data remaining from the six projects—four dense-graded and two gap-graded—showed no statistical difference in the average surface permeability of HMA and RHMA-G when tested at the 95% confidence level.

On four of the seven projects, including all three of the RHMA-G sections, testing in both directions and in both wheelpaths locations showed no statistical difference in surface permeability. But, one HMA project showed dissimilarity in both directions and in the wheelpaths. Five pairs of cores from this project were then tested for permeability and specific gravity in the laboratory. Unfortunately, no conclusions could be drawn due to a lack of spatial information; however one of the five locations had very little variability between core pairs in either specific gravity or permeability, while another location had significant differences between the specific gravity and permeability measurements.

When data from this dense-graded hot mix asphalt surface were removed along with the data from the one gap-graded rubberized hot mix asphalt surface with very high permeability, the remaining five projects—three dense-graded and two gap-graded—again showed no statistical difference in the average surface permeability of HMA (3.3E-4 cm/sec) and RHMA-G (4.2E-4 cm/sec) when tested at the 95% confidence level. It is recommended that testing of more RHMA-G mixes may be warranted to see if the high permeability on one mix in this study is unique. Construction QC/QA should also be examined to see if that mix met compaction specifications.

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No proposals for implementation. Testing of some more RHMA-G mixes may be warranted to see if the high permeability on one mix in this study is unique. Construction QC/QA should also be examined to see if that mix met compaction specifications.

8. RELATED DOCUMENTS
None

9. LABORATORY ACCREDITATION
The UCPRC laboratory is accredited by AASHTO re:source for the tests listed in this report

10. SIGNATURES

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

PROJECT OBJECTIVES/GOALS

The entry of water into dense-graded hot mix asphalt and gap-graded rubberized hot mix asphalt can damage asphalt-aggregate adhesion and reduce the strength of the mix, and eventually strip binder from the aggregates resulting in early failure.

The ability of water to enter the pavement surface and laterally move throughout the mix was measured with the National Center for Asphalt Technology (NCAT) field permeameter. The permeability of these two asphalt pavement mix types was compared across several projects constructed within the past two years.

The following tasks were conducted in order to complete this comparison:

- Task 1: Field testing, to measure field surface permeability on seven projects
- Task 2: Lab testing, to assess surface permeability and material specific gravity on one project
- Task 3: Reporting, completed with this technical memorandum

LIST OF ABBREVIATIONS

BWP	Between Wheelpaths
HMA	Hot mix asphalt
NCAT	National Center for Asphalt Technology
PM	Post Mile
RHMA-G	Rubberized HMA—Gap-Graded
RWP	Right Wheelpath

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	inches	25.4	Millimeters	mm
Ft	feet	0.305	Meters	m
Yd	yards	0.914	Meters	m
Mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
Ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
Gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
Oz	ounces	28.35	Grams	g
Lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
Fc	foot-candles	10.76	Lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
Lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
Km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003)

1 INTRODUCTION

1.1 Background to the Study

In addition to supporting loads, the role of the pavement surface is to maintain a moisture barrier that protects the underlying pavement material from the environment. Dense-graded hot mix asphalt (HMA), which constitutes surface layers in an asphalt pavement structure, is expected to be impermeable enough to prohibit water from entering the structure and damaging the asphalt layers, and from passing through the HMA layers and damaging the unbound layers below. In California, rubberized hot mix asphalt with gap-graded aggregate (RHMA-G) has often been used as a surface course mix for several reasons: it decreases the required structural thickness when used to retard reflective cracking, decreases noise generated from the interaction of tire and pavement, and encourages the use of recycled vehicle tires.

The California Department of Transportation (Caltrans) is interested in the continued use of RHMA-G as a surface mix for flexible pavements. The bituminous material uses ground rubber from recycled tires, and requires half the thickness needed for HMA for thin overlays placed on cracked pavement *(1)*. However, RHMA-G constructed using Caltrans method specifications has typically resulted in high air-void contents and high permeability compared with HMA. The air-void contents and permeability in the wheelpaths tended to be reduced within two years of construction due to compaction by traffic, while the permeability outside of the wheelpaths typically remained high *(2)*. In 2015 Caltrans implemented QC/QA compaction specifications for RHMA-G to replace method specifications, expecting that this would lower air-void contents and permeabilities. And in late 2015, the Caltrans Office of Asphalt Pavements requested that several projects be tested to compare the surface permeabilities of recently constructed HMA and RHMA-G pavement surfaces.

1.2 Project Scope

Seven projects, completed since 2015 and located within 100 miles of Sacramento (in Caltrans District 3 and District 4), were selected as subjects for comparing surface permeability. Four projects were surfaced with HMA, and three were surfaced with RHMA-G. When one of these HMA projects became inaccessible due to weather, an active HMA project from District 9 was substituted. All seven projects were field tested for surface permeability.

In addition, Caltrans personnel sampled cores from the District 9 project to determine whether differences in the density of these cores could be estimated using measured permeability values. The UCPRC laboratory tested these cores for density and permeability using the NCAT permeameter.

1.3 Overview

Field testing and a comparison of the permeability of the RHMA-G and HMA surfaces for the seven projects are presented in Chapter 2. Chapter 3 presents the analysis of the laboratory data on HMA cores taken from the Mono 120 project in District 9. A complete summary of the work done and suggestions for further work are provided in Chapter 4. Appendixes A through C provide supporting documentation and the details of the test results.

2 FIELD TESTING

Seven locations were tested in the field with the NCAT field permeameter. The testing was conducted between December 2015 and March 2016, with daytime temperatures in the upper 50s to low 60s (degrees Fahrenheit). Traffic control was provided by Caltrans Maintenance. The field test data is presented in Section 2.2 and a summary analysis is presented in Section 2.3.

2.1 Project and Testing Location

As noted, six of the seven projects were located in Caltrans Districts 3 and 4, within 100 miles of the San Francisco Bay and Sacramento areas, and the seventh was in District 9. Table 2.1 presents the project locations, along with the closest Caltrans Maintenance Station, the Expenditure Authorization (EA) Number, Contract Acceptance Date, and Project ID used throughout this memo.

Table 2.1: Project Locations for Permeability Testing

County	Route	Start PM	End PM	Maintenance Station	District–Caltrans EA	Acceptance Date	Project ID
Placer	174	0.0	2.8	Auburn	03-4M5704	10/4/2013	Pla174
Butte	191	0.2	11.4	Chico	03-4M2704	10/31/2013	But191
Sacramento	160	R0.0	12.0	Rio Vista	03-2F9904	9/8/2015	Sac160
Yuba	20	0.8	R2.0	Marysville	03-0A5804	8/13/2015	Yub20
Santa Clara	152	R9.9	21.9	Gilroy	04-4C2004	11/4/2015	SCl152
Solano	680	0.35	13.1	Benicia	04-3G6504	2/2/2016	Sol680
Mono	120	43.0	45.1	Bishop	09-359904	9/19/2016	Mno120

Table 2.2 shows the surface material, limits of sampling, sampling date, and ambient weather conditions experienced during field permeameter testing.

Table 2.2: Project Surface Material and Sampling Details

Project ID	Surface Material	Sampling Start PM	Sampling End PM	Sampling Date	Temperature and Weather
Pla174	RHMA-G	1.7	2.7	12/2/2015	59°F, Partly Cloudy
But191	RHMA-G	6.5	7.5	12/8/2015	58°F, Partly Cloudy
Sac160	RHMA-G	6.0	7.0	12/14/2015	58°F, Partly Sunny
Yub20	HMA	R1.6	R2.0	12/16/2015	52°F, Clear, Sunny
SCl152	HMA	19.9	20.9	1/15/2016	59°F, Overcast
Sol680	HMA	6.0	7.0	2/23/2016	62°F, Cloudy
Mno120	HMA	44.0	44.5	3/2/2016	65°F, Clear, Sunny

For most locations, tests were conducted at 200 meter intervals to cover a mile-long section. At each interval, tests were conducted in the right wheelpath (RWP) and between the left and right wheelpaths (BWP), and in both traffic directions when possible. The following were exceptions: both Yuba 20 and Mono 120 had test sections less than one mile long, and on Santa Clara 152 the sampling was restricted to one direction.

2.2 Field Test Data

All the permeability values calculated from field testing are shown in Figure 2.1 and can be found in Tables A.1 through A.7 of Appendix A, from the transcribed field data worksheets. The data are grouped by project and the projects have been split between those surfaced with HMA and those with RHMA-G. Each project site has been further divided by direction and wheelpath. The primary direction is either northbound or eastbound (NB or EB), and the secondary direction is either southbound or westbound (SB or WB). The wheelpath is either in the right wheelpath (RWP) or between the wheelpaths (BWP). As shown, Santa Clara 152 (SCl152), has a surface material of HMA, and was only tested in the primary direction.

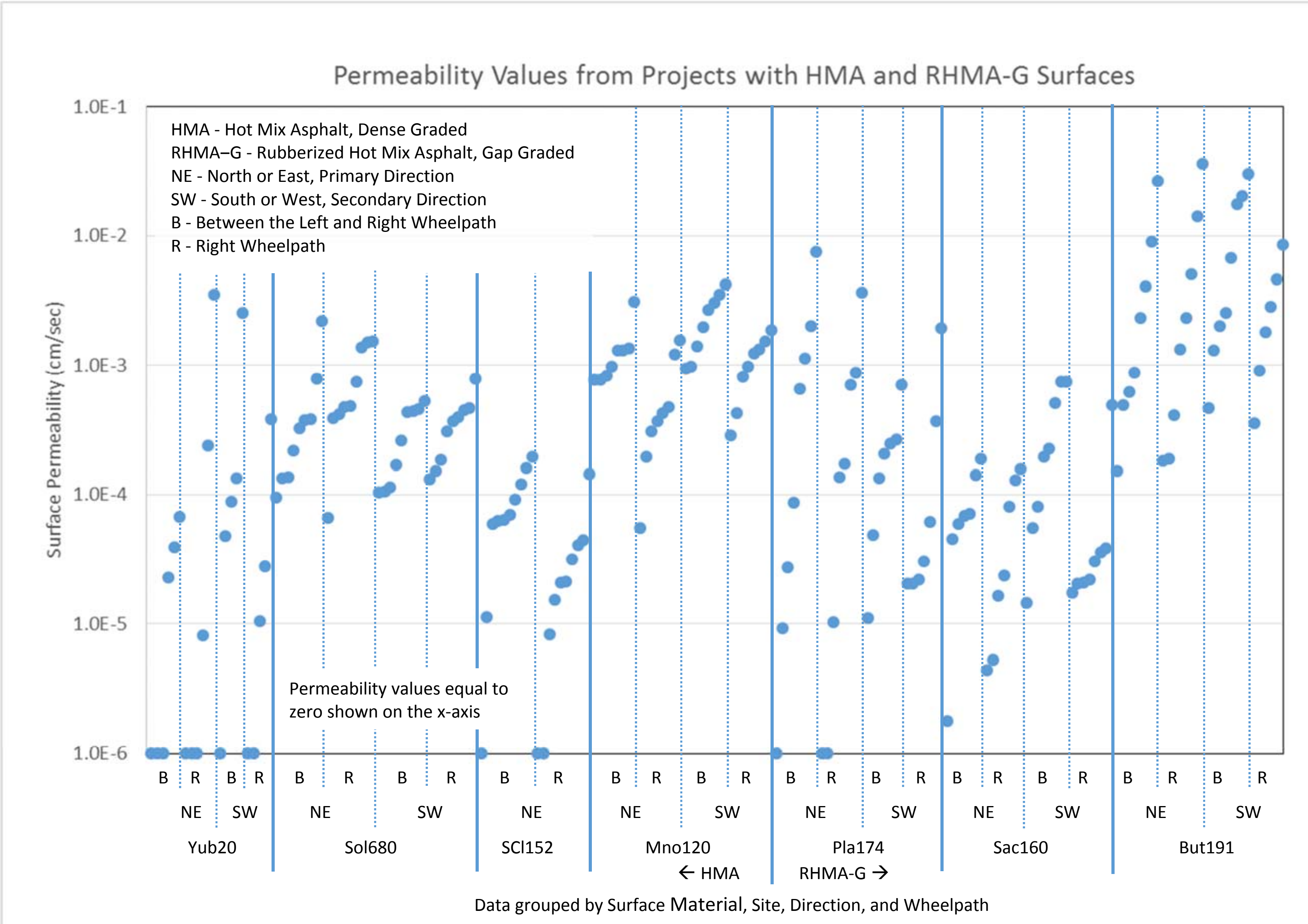

Figure 2.1: Permeability values from projects with HMA and RHMA-G surfaces.

2.3 Analysis of Field Surface Permeability Data

Figure 2.2 shows the cumulative distribution of all the data collected from each surface material, HMA and RHMA-G. According to t-tests run at the 95% confidence level, the mean values of permeability for HMA (6.1E-4 cm/sec) and RHMA-G (2.9E-3 cm/sec) are statistically different. For both data sets, the standard deviation (HMA: 8.5E-4 cm/sec and RHMA-G: 6.8E-3 cm/sec) is larger than the mean value, so values of zero permeability are reasonable—though they cannot be shown on the logarithmic plot.

The median value for HMA permeability (2.9E-4 cm/sec) is 38 percent greater than that of RHMA-G (2.1E-4 cm/sec). And the first quartile value for HMA permeability (6.0E-5 cm/sec) is 62 percent greater than RHMA-G permeability (3.7E-5 cm/sec). However, the third quartile values show the RHMA-G permeability (1.8E-3 cm/sec) is 225 percent greater than the HMA permeability (8.0E-4 cm/sec). It can be seen that several large permeability values for RHMA-G produce a divergence in the distributions.

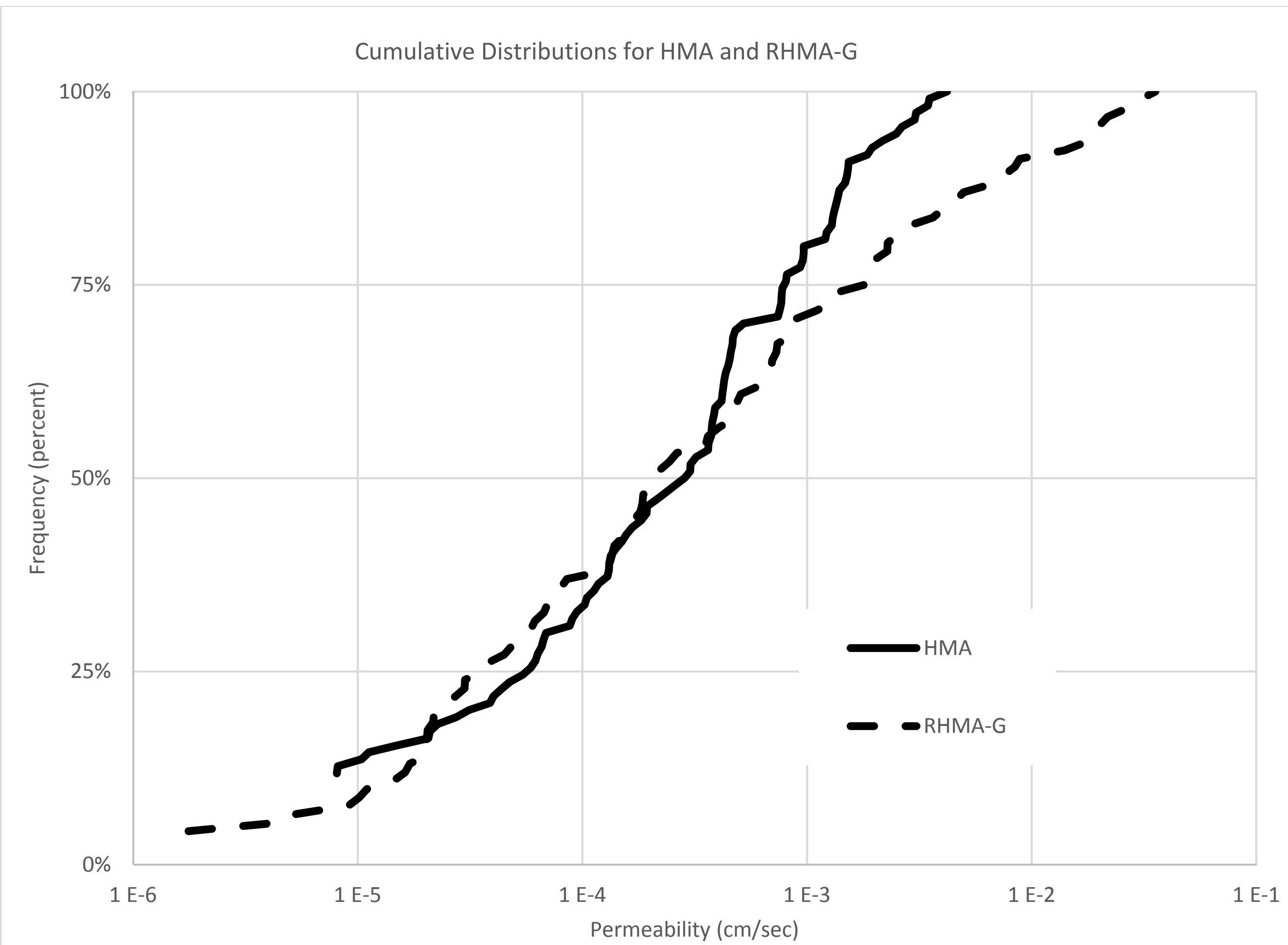

Figure 2.2: Cumulative distributions for all the HMA data and RHMA-G data.

2.3.1 Comparisons of HMA and RHMA-G

Figure 2.3 presents the average values from the data shown in Figure 2.1, and Table 2.3 provides the average permeability values from the sections tested, with the RHMA-G projects shown below the HMA projects. The averages of each surface mix are shown bold and *italicized* below each group of projects. For each section bolded in the first column, the average permeability for that location is shown in the last column of the same row. Below that section average is the averages for each direction, with the primary direction, north or east, shown first. Averages are also provided for each wheelpath in the middle two columns, with the section averages shown in the same row as the section name and are subgroup within each direction and wheelpath.

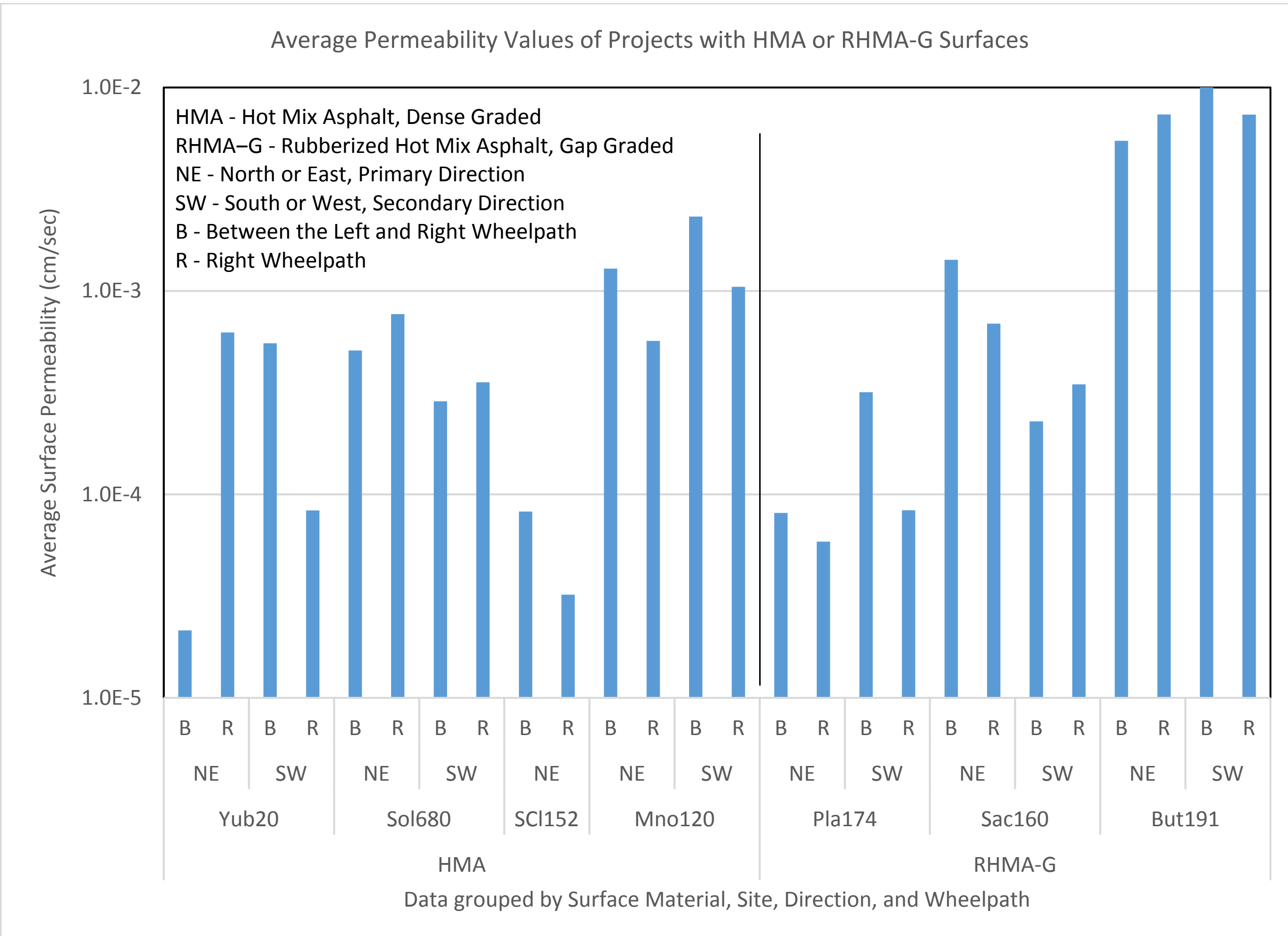

Figure 2.3: Average permeability values from projects with HMA or RHMA-G surfaces.

Table 2.3: Average Permeability Values for All Projects (cm/sec)

Location / Direction	BWP	RWP	Average
Yub20	2.6 E-4	3.8 E-4	**3.2 E-4**
EB	2.1 E-5	6.2 E-4	3.2 E-4
WB	5.5 E-4	8.3 E-5	3.2 E-4
Sol680	4.0 E-4	5.6 E-4	**4.8 E-4**
NB	5.1 E-4	7.7 E-4	6.4 E-4
SB	2.9 E-4	3.6 E-4	3.2 E-4
SCl152	8.2 E-5	3.2 E-5	**5.7 E-5**
EB	8.2 E-5	3.2 E-5	5.7 E-5
Mno120	1.8 E-3	8.1 E-4	**1.3 E-3**
EB	1.3 E-3	5.7 E-4	9.3 E-4
WB	2.3 E-3	1.0 E-3	1.7 E-3
All HMA Materials	*7.2 E-4*	*5.0 E-4*	***6.1 E-4***
Pla174	2.1 E-4	7.2 E-5	**1.4 E-4**
EB	8.1 E-5	5.9 E-5	7.0 E-5
WB	3.2 E-4	8.3 E-5	2.0 E-4
Sac160	8.6 E-4	5.3 E-4	**7.0 E-4**
EB	1.4 E-3	6.9 E-4	1.1 E-3
WB	2.3 E-4	3.5 E-4	2.9 E-4
But191	7.8 E-3	7.4 E-3	**7.6 E-3**
NB	5.5 E-3	7.4 E-3	6.4 E-3
SB	1.0 E-2	7.4 E-3	8.7 E-3
All RHMA-G Materials	*3.1 E-3*	*2.8 E-3*	***2.9 E-3***

Note: For each project bolded in the first column, the average permeability for that location is shown in the last column of the same row. Below the project average is the average for each direction. Averages are also provided for each wheelpath in the middle two columns, with the project averages shown in the same row as the project name. The averages of each surface mix are shown bold and italicized below each group of projects.

Some simple observations from looking at Figure 2.3 and Table 2.3: the average permeability on Santa Clara 152 (5.7E-5 cm/sec) is the lowest of all the projects, and that on Butte 191 (7.6E-3 cm/sec) is the highest. The average permeability on Mono 120 (1.3E-3 cm/sec) is twice the average for HMA projects, and four times greater than the remaining HMA projects (3.3E-4 cm/sec). And the permeability on Butte 191 is eighteen times greater than on the remaining RHMA-G projects (4.2E-4 cm/sec).

A larger sample size for each surface mix type would provide more confidence in the results of statistical analysis considering the variability in the data and the possibilities for differences between projects for a given mix type as shown by the results found in this study. Figure 2.4, which is based on data collected on an earlier project at the UCPRC *(2)*, shows that surface permeabilities up to 1.0E-1 cm/sec can be expected for RHMA-G in the first year when compacted with the method specification, but after one year the permeability falls below 1.0E-2 cm/sec for RHMA-G because of densification under traffic in the wheelpaths. The areas outside the wheelpaths remained at the constructed high permeability. The RHMA-G projects in that previous study were built prior to Caltrans implementation of QC/QA testing for RHMA-G, using a method compaction specification. The HMA permeability values in that study were consistently below 1.0E-2 cm/sec regardless of age *(2)*. It is not certain whether the RHMA-G surface of Butte 191 was built under the QC/QA or the method compaction specification.

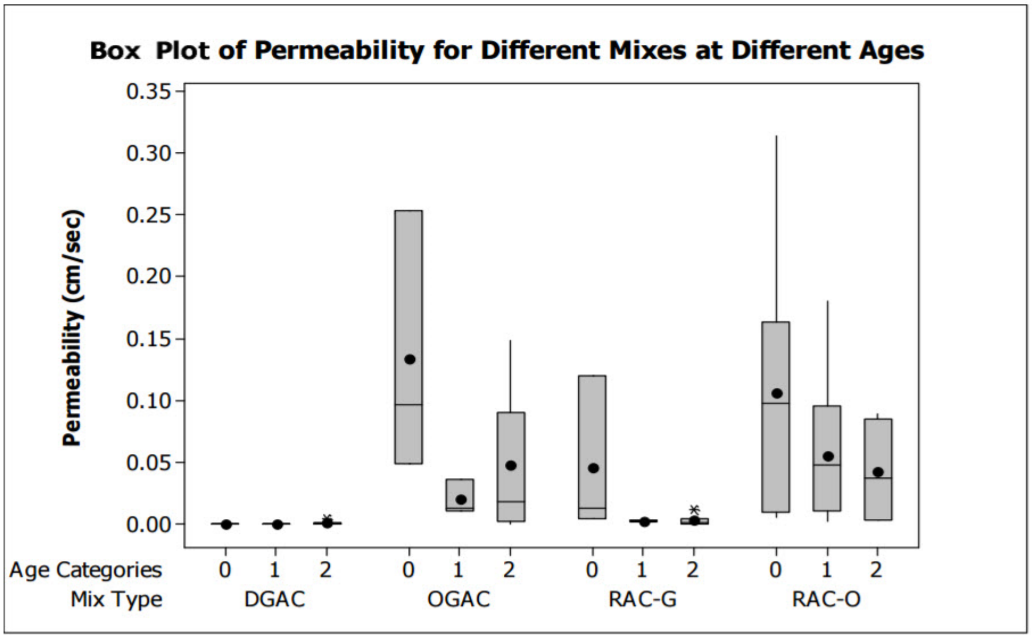

Figure 2.4: Box plot of permeability values from different mix types and ages.
(Note: age Category 0 is less than one year old, Category 1 is one to four years old, and Category 2 is older than four years old.) ***(2)***

As mentioned, the average permeability measured on Butte 191 was the highest among the projects tested. Seven of the thirty-two measurements on the project were above 1.0E-2 cm/sec, a permeability not measured on any other project. Because of this difference in the measured permeabilities, another comparison of the surface material was performed that excluded the Butte 191 data.

Figure 2.5 presents the cumulative distributions for all the HMA and RHMA-G data, as shown in Figure 2.2, along with the same distributions with one project removed from each material. The Mono 120 and Butte 191 data have been removed from the HMA and RHMA-G data, respectively.

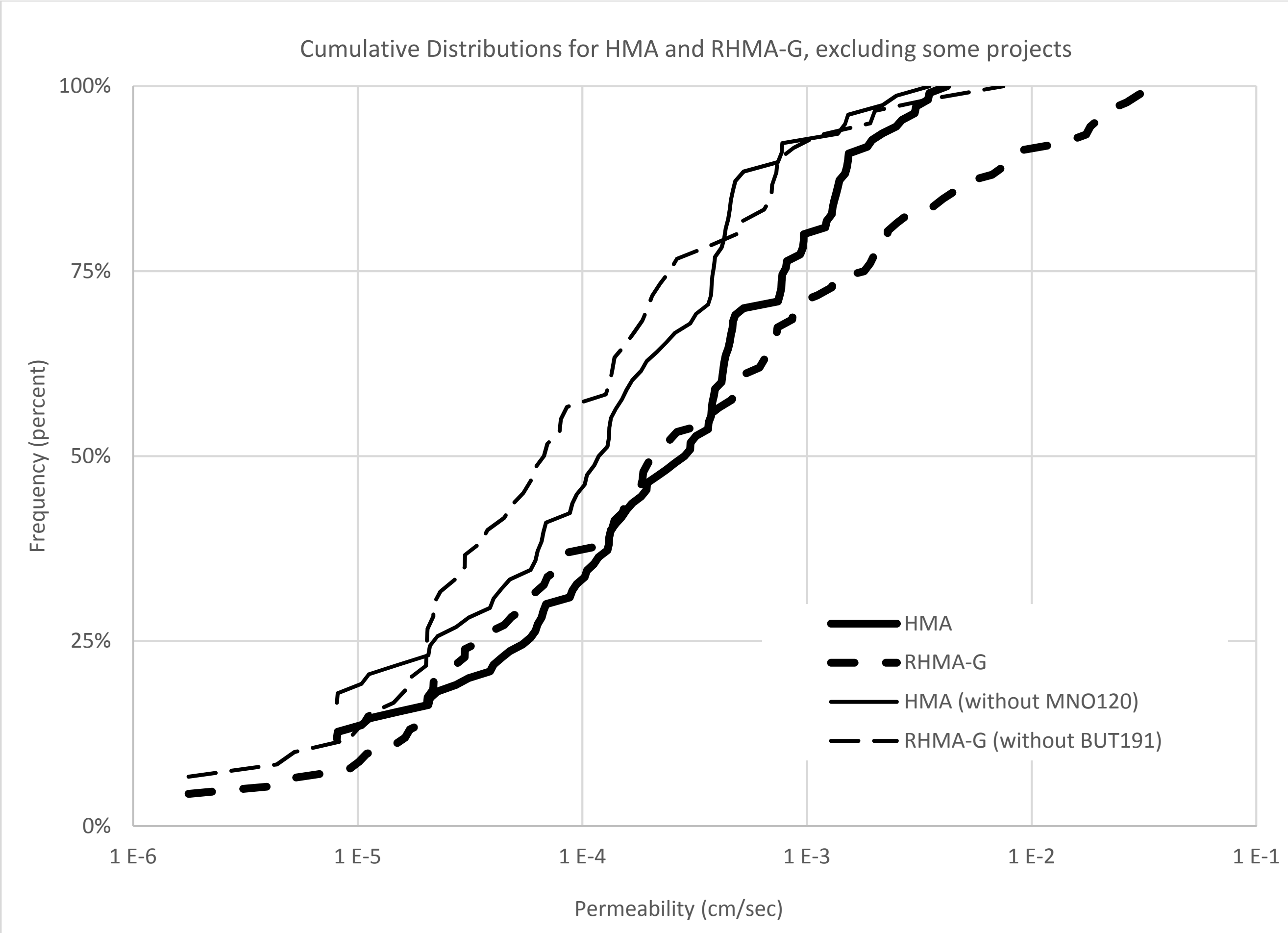

Figure 2.5: Cumulative distributions for the HMA data and RHMA-G data, excluding some projects.

While removing the Mono 120 data does not change the statistical similarity of the two materials, the average value for the permeability is reduced by 45 percent, from 6.1E-4 cm/sec to 3.3-E-4 cm/sec. The reduction in the quartile values show the overall HMA distribution is reduced by 50 to 60 percent, but the shape of the HMA distribution is similar with and without the Mono 120 data.

The change in RHMA-G distribution after removal of the high permeabilities of the Butte 191 project is more apparent. The reduction in the first quartile is 45 percent, and 85 percent for the third quartile, indicating a change in the shape of the distribution. And the median and average values decrease by 68 and 86 percent, respectively, exhibiting the shift left, especially above the 50^{th} percentile. However, the highest permeability values still come from RHMA-G surfaces.

Regardless, the change in the RHMA-G distribution is consequential. Table 2.4 presents a summary of the statistical tests conducted on the data sets, with and without data from Mono 120 and Butte 191. The test results show that, with the Butte 191 data removed, the surface permeabilities from HMA and RHMA-G are similar, regardless of whether the Mono 120 data is removed.

Table 2.4: Statistical t-test Results (α = 5%) Comparing Material Datasets

Data Set	HMA		HMA, excluding Mno120	
	t-Stat	t-Critical	t-Stat	t-Critical
RHMA-G	-3.22183	1.98580	-3.62984	1.98580
	Significant		Significant	
RHMA-G, excluding But191	1.17791	1.98447	-0.58115	1.98861
	Not Significant		Not Significant	

Table 2.5 presents the data averages from Table 2.3 with the exclusion of data from the Butte 191 and Mono 120 projects.

2.3.2 Comparisons of Direction and Wheelpath

For individual locations, comparisons of surface permeability were made between the primary (northbound or eastbound) direction and the secondary (southbound or westbound) direction, and between the right wheelpath and between the wheelpaths. These statistical comparisons—t-tests for equal means, assuming unequal variances, at the 95% confidence interval—are presented in Appendix B.

Four of the seven projects (Yuba 20, Placer 174, Butte 191, and Sacramento 160) exhibit no statistical difference in the surface permeability between the two directions or between the two wheelpaths. Solano 680 and Mono 120 both show a statistical difference in the surface permeability between the two directions. And for both Mono 120 and Santa Clara 152, there is a statistical difference between the right wheelpath and between the wheelpaths.

Table 2.6 shows those locations with the statistical results where there are differences in direction and wheelpath permeability values. However, only for Mono 120 do the t-statistic and t-critical values differ by more than 0.1. The differences for Solano 680 and Santa Clara 152 would not be statistically significant at a 99% confidence level.

Table 2.5: Average Permeability Values (cm/sec) with Revised Averages Showing Effects of Excluding Mono 120 and Butte 191

Location / Direction	BWP	RWP	Average
Yub20	2.6 E-4	3.8 E-4	**3.2 E-4**
EB	2.1 E-5	6.2 E-4	3.2 E-4
WB	5.5 E-4	8.3 E-5	3.2 E-4
Sol680	4.0 E-4	5.6 E-4	**4.8 E-4**
NB	5.1 E-4	7.7 E-4	6.4 E-4
SB	2.9 E-4	3.6 E-4	3.2 E-4
SCl152	8.2 E-5	3.2 E-5	**5.7 E-5**
EB	8.2 E-5	3.2 E-5	5.7 E-5
Three HMA Projects	2.8 E-4	3.7 E-4	**3.3 E-4**
Mno120	1.8 E-3	8.1 E-4	**1.3 E-3**
EB	1.3 E-3	5.7 E-4	9.3 E-4
WB	2.3 E-3	1.0 E-3	1.7 E-3
Four HMA Projects	*7.2 E-4*	*5.0 E-4*	***6.1 E-4***
Pla174	2.1 E-4	7.2 E-5	**1.4 E-4**
EB	8.1 E-5	5.9 E-5	7.0 E-5
WB	3.2 E-4	8.3 E-5	2.0 E-4
Sac160	8.6 E-4	5.3 E-4	**7.0 E-4**
EB	1.4 E-3	6.9 E-4	1.1 E-3
WB	2.3 E-4	3.5 E-4	2.9 E-4
Two RHMA-G Projects	*5.4 E-4*	*3.0 E-4*	***4.2 E-4***
But191	7.8 E-3	7.4 E-3	**7.6 E-3**
NB	5.5 E-3	7.4 E-3	6.4 E-3
SB	1.0 E-2	7.4 E-3	8.7 E-3
Three RHMA-G Projects	*3.1 E-3*	*2.8 E-3*	***2.9 E-3***

Note: For each project bolded in the first column, the average permeability for that location is shown in the last column of the same row. Below the project average is the average for each direction. Averages are also provided for each wheelpath in the middle two columns, with the project averages shown in the same row as the project name. The averages of each surface mix are shown bold and italicized below each group of projects.

Table 2.6: Locations with t-test Results (α = 5%) Showing Statistical Differences

Location	Direction Comparison		Wheelpath Comparison	
	t Stat	t Critical	t Stat	t Critical
Solano 680	2.1537	2.0860	-	-
Santa Clara 152	-	-	2.1757	2.1199
Mono 120	-2.2726	2.0555	3.1969	2.0739

Figure 2.6 through Figure 2.8 show the individual field results for the three projects listed in Table 2.6.

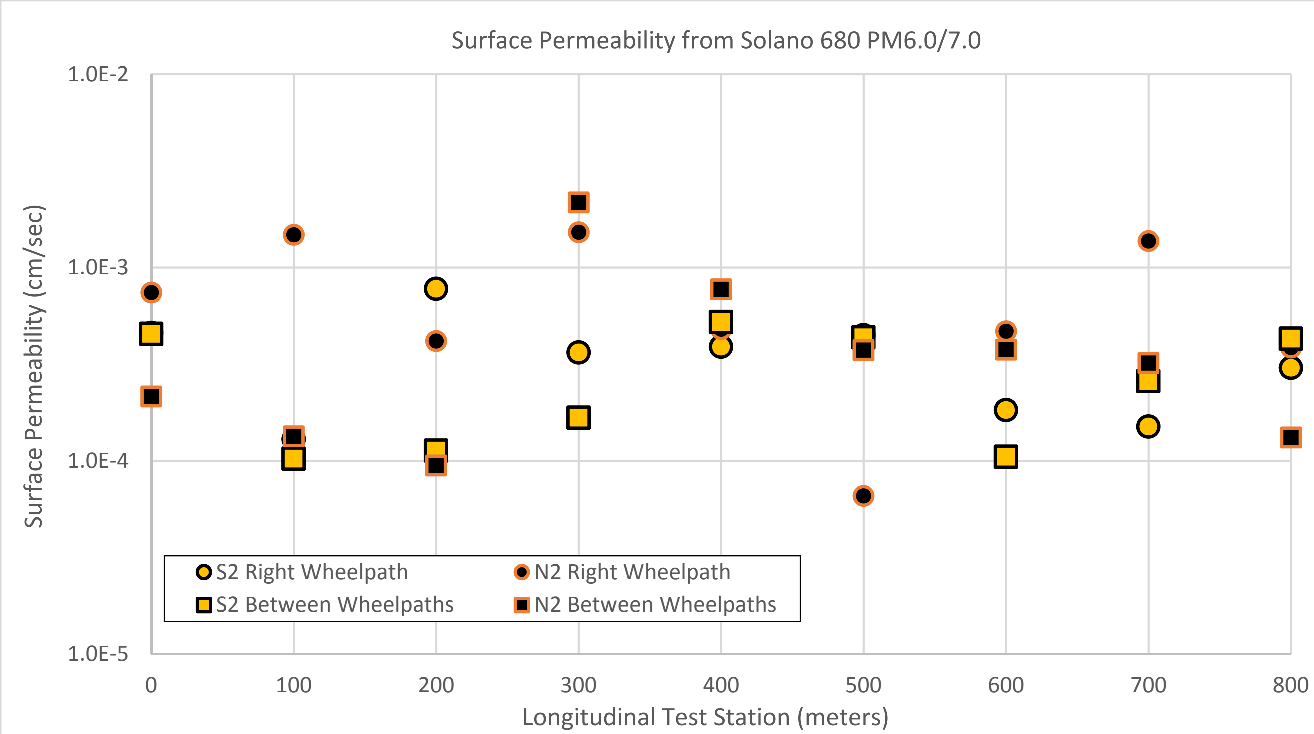

Figure 2.6: Surface permeability from Solano 680, PM6.0/7.0.

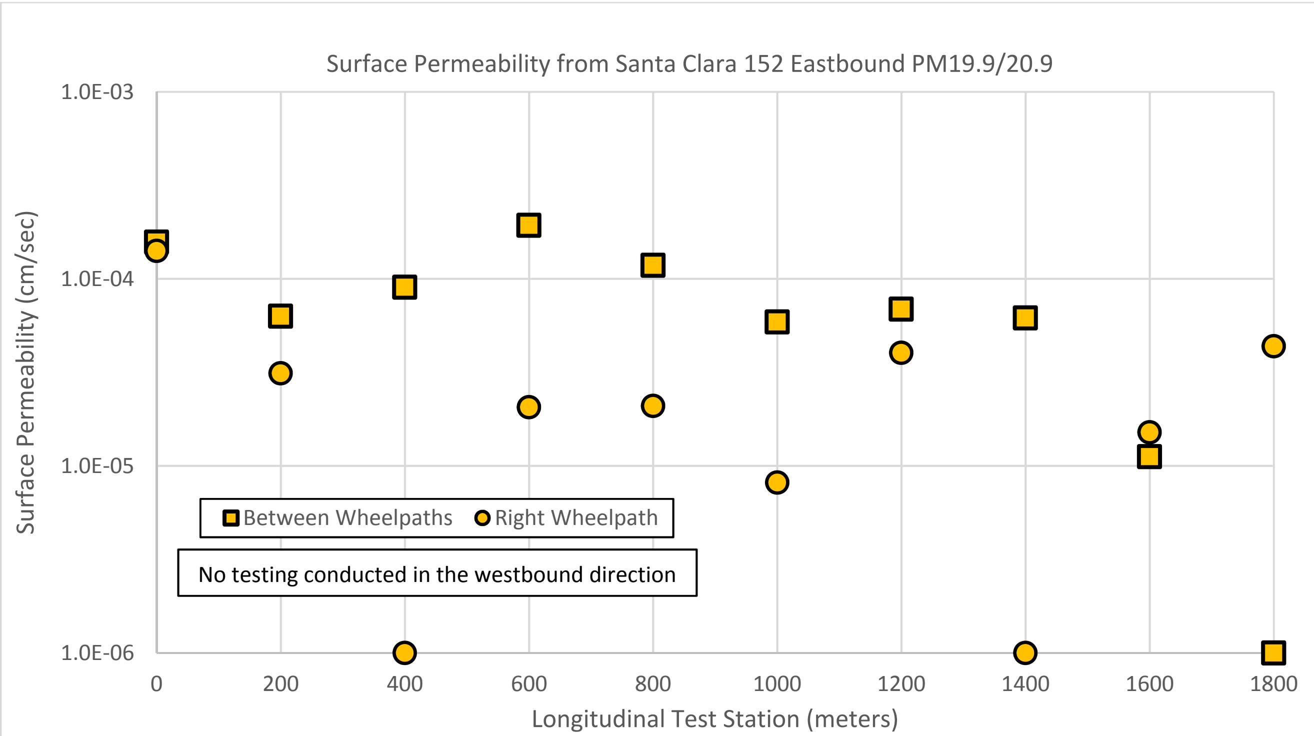

Figure 2.7: Surface permeability from Santa Clara 152 eastbound, PM19.9/20.9.

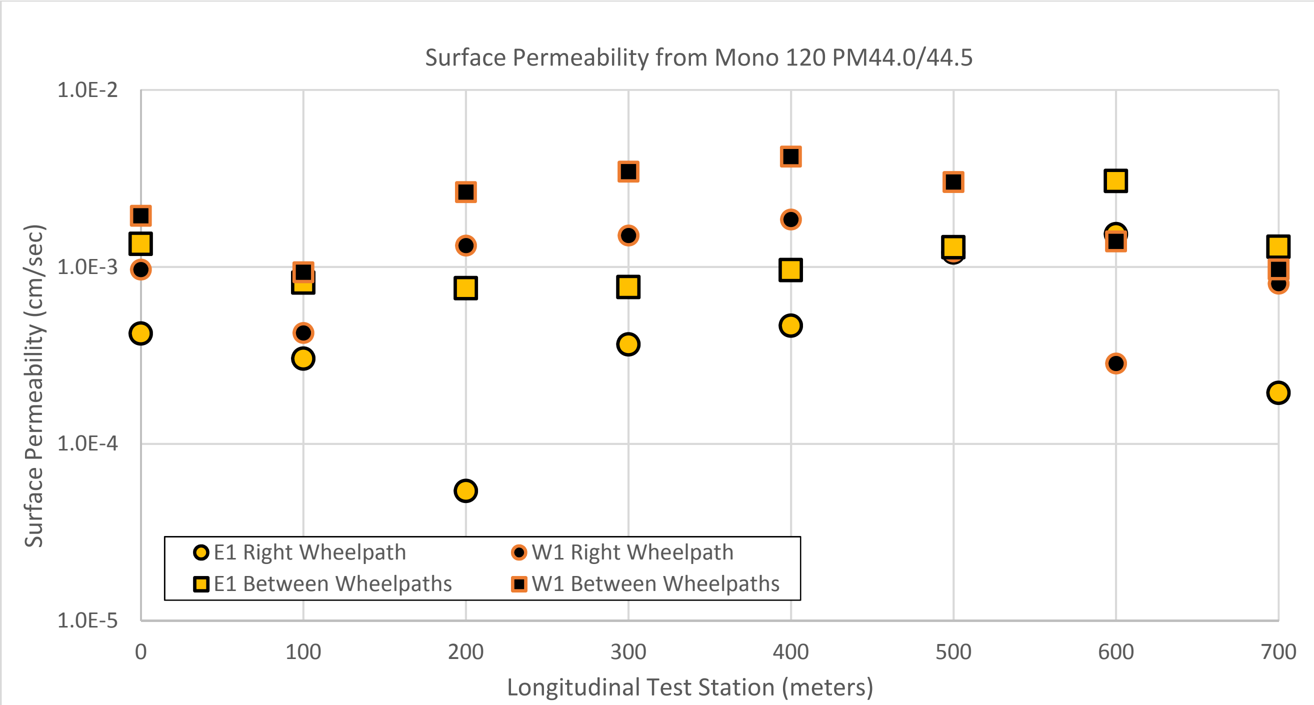

Figure 2.8: Surface permeability from Mono 120, PM44.0/44.5.

Because the data from Mono 120 show differences between the two directions and between the wheelpath values, one comparison of the surface material includes the Mono 120 data and another excludes the Mono 120 data.

The average permeability value for the gap-graded (RHMA-G) mixes, 2.9E-3 cm/sec, is almost five times greater than for the dense-graded (HMA) mixes, 6.1E-4 cm/sec, when the Mono 120 data is included. Excluding the Mono 120 data lowers the average dense-graded permeability to 3.3E-4 cm/sec, showing that the gap-graded mixes are nine times more permeable than the dense-graded mixes.

With or without the Mono 120 data, the surface permeameter values show a statistical difference, at the 95% confidence level, between the projects with RHMA-G surfaces and those with HMA surfaces. The statistical test is shown in Appendix B.3.

3 LAB TESTING ON MONO 120 CORES

3.1 Mono County 120

As a follow-up on the Mono 120 field testing, Caltrans provided 10 cores from the project for additional permeability testing in the laboratory to evaluate whether a relationship exists between surface permeability and specific gravity. Two cores were provided from five locations but without any accompanying information about relationships between the locations or the core pairs, about which directions the cores came from, or the distances between locations. Further, no information was provided about whether the core pairs originated from the wheelpath or from outside the wheelpath, or any other relationship.

The NCAT falling head permeameter was used in the laboratory to measure the permeability of the cores. In this procedure, the sides of the core are sealed to only permit vertical water flow which should result in lower permeability than would be measured in the field where water is allowed to flow laterally once it passes through the pavement surface. Three replicate tests were run with the results averaged to produce a single permeability value for each specimen. The bulk specific gravity was also measured for each core using AASHTO T 331. Insufficient material was available to perform tests for Maximum Theoretical Density and therefore air-void contents could not be calculated.

3.2 Lab Test Data

The falling head permeability and bulk specific gravity data are presented below in Table 3.1.

Table 3.1: Data from Permeability and Specific Gravity Testing on Mono 120 Cores

Core ID	Location and Core Number	Permeability (cm/sec)	Bulk Specific Gravity
Core 1-4	Location #1 – Core 4	3.7E-4	2.11
Core 1-8	Location #1 – Core 8	8.2E-5	2.13
Core 2-4	Location #2 – Core 4	1.7E-5	2.02
Core 2-8	Location #2 – Core 8	2.2E-4	1.99
Core 3-3	Location #3 – Core 3	6.9E-6	1.98
Core 3-9	Location #3 – Core 9	6.6E-6	1.98
Core 4-8	Location #4 – Core 8	2.2E-6	1.97
Core 4-9	Location #4 – Core 9	6.8E-7	1.99
Core 5-7	Location #5 – Core 7	7.9E-5	2.08
Core 5-8	Location #5 – Core 8	4.5E-5	2.10

The original location (direction, wheelpath) of the cores was unknown to the laboratory, so no detailed comparison was made between the field test results and the lab test results. The average permeability measured in the field equaled 1.3E-3 cm/sec, while the average permeability for the laboratory tests was 8.4E-5 cm/sec. This difference is likely due to the required vertical flow of water through the laboratory tests, while water could flow vertically and horizontally in the field tests.

3.3 Lab Data Analysis

Figure 3.1 presents the permeability and specific gravity values for the 10 specimens shown in Table 3.1. On average, the core pairs from each location (i.e., Core 3-3 and Core 3-9) had specific gravities within 1 percent, while the permeability values from the core pairs varied by 350 percent. From this, it is difficult to see a direct relationship between specific gravity and permeability. And looking at the data shown in Figure 3.1, the results do not show a strong relationship between specific gravity and permeability.

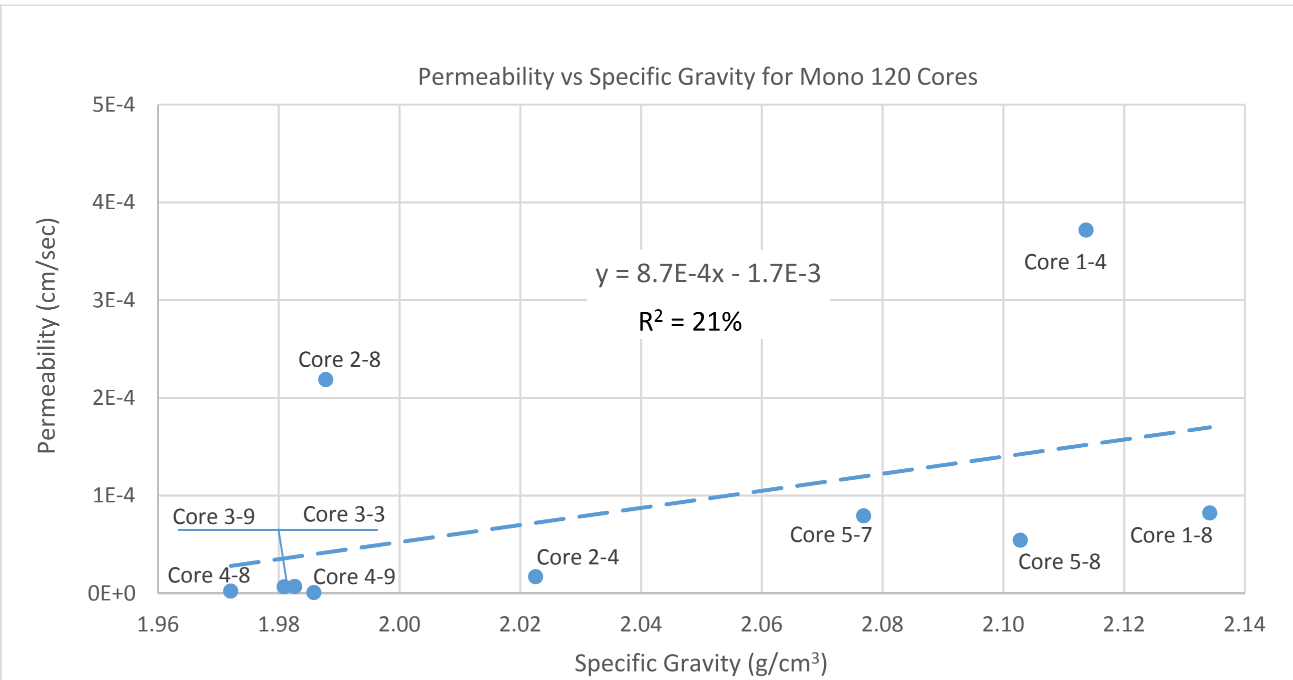

Figure 3.1. Specific gravity versus permeability of Mono 120 cores.

The pairs from Location 1 and Location 2 showed the largest differences between the cores in permeability and specific gravities—excluding the specific gravities of Location 5. Figure 3.1 shows a linear relationship with all 10 data points.

Figure 3.2 shows the regression with two extreme permeability points removed, Core 1-4 and Core 2-8. The regression results show a much stronger relationship between permeability and specific gravity with the outliers removed. If all four cores from Location 1 and Location 2 are removed, the regression results are similar.

A positive relationship between permeability and specific gravity was identified by the regression, which is the opposite of what was expected. However, for these cores with this level of density, the permeability of mixes was less than 1.0E-4 cm/sec, which is basically impermeable. This information indicates that permeability is not a good indicator of specific gravity.

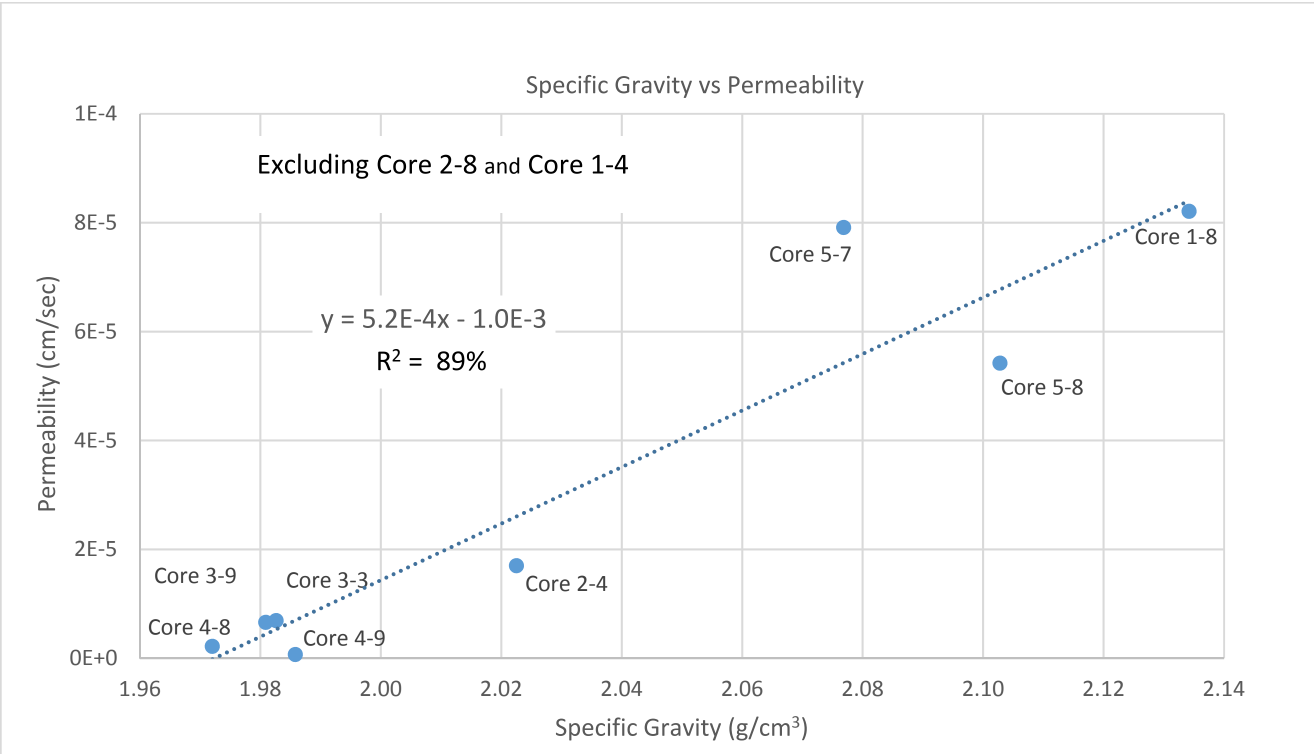

Figure 3.2. Specific gravity versus permeability of Mono 120 cores, excluding Core 1-4 and Core 2-8.

4 SUMMARY AND CONCLUSIONS

4.1 Summary

The surface permeability of four dense-graded hot mix asphalt (HMA) projects was compared with the surface permeability of three gap-graded rubberized hot mix asphalt (RHMA-G) projects using the National Center for Asphalt Technology (NCAT) field permeameter. The average permeability of the projects with an HMA surface was 6.1E-4 cm/sec. The average permeability of the projects with an RHMA-G surface was 2.9E-3 cm/sec. One project of each material type produced data that differed from that of the other projects with same material. One RHMA-G project, Butte 191, exhibited the highest permeability values of this study, values that may not be representative. The average permeability of the RHMA-G surfaces excluding the Butte 191 data was 4.2E-04 cm/sec.

The data were compared using Student *t*-tests assuming unequal variances with an alpha value of 0.05. When data from two potentially outlier projects are not removed, the data set shows a difference between RHMA-G and HMA at the 95 percent confidence level. When one of the seven projects, Butte 191 with an RHMA-G material and much greater permeability than the other projects, is removed from the data set the study shows that statistical differences between RHMA-G and HMA are not significant at the 95 percent confidence interval.

One HMA project, Mono 120, displayed field permeability values with differences both between the directions of travel and when right wheelpath measurement values were compared with those from between the wheelpaths. While removing the Mono 120 data does not change the statistical similarity of the HMA and RHMA-G surface, the average surface permeability of HMA excluding the Mono 120 data was almost halved to 3.3E-4 cm/sec.

Three of the four projects with HMA surfaces showed a statistically significant difference, at the 95% confidence level, in comparisons of road directions (e.g., eastbound versus westbound) and in comparisons of measurements taken in the right wheelpath versus those taken between the wheelpaths. This indicates additional densification by traffic after construction. Santa Clara 152 exhibited a significant difference in a comparison of wheelpath measurements versus those taken between the wheelpath and Solano 680 showed differences in a comparison of directions, while Mono 120 produced differences in both comparisons.

All three of the projects surfaced with RHMA-G showed no statistical differences when comparing the direction of travel and wheelpath impacts.

Ten HMA core samples, consisting of five pairs, were collected by Caltrans from the Mono County 120 project, and laboratory tests of specific gravity and permeability were performed on the cores by UCPRC. Specific gravity and permeability testing in the laboratory showed differences in some locations where core pairs were sampled. However, due to a lack of information regarding the relative source locations of these cores, further analysis is only speculative.

The test results showed that two of the five pairs, the cores from Locations 3 and 4, exhibited a high degree of uniformity, with similar specific gravity and permeability values. Another two pairs, cores from Locations 1 and 2, showed a difference in terms of permeameability values, while the pairs from Locations 2 and 5 showed a significant difference in terms of specific gravity. The variability of the permeability and specific gravity results at Location 2 may indicate a lack of uniformity of its surface layer.

The positive correlation of specific gravity and permeability is the opposite of what was expected, as normally permeability is expected to decrease as specific gravity increases. However, at this level of density, the permeability of the HMA is effectively zero, rendering correlations essentially meaningless and of little importance.

4.2 Conclusions

The following conclusions have been drawn from this limited study:

1. The surface permeability of HMA and RHMA-G are statistically similar when the Butte 191 RHMA-G data are removed.
2. The reasons why the Butte 191 mix has much higher permeability should be explored further.
3. For the pavements tested, there was little difference when data from both directions of traffic were compared and when the measured values from within the right wheelpath and between the two wheelpaths were compared.
4. Permeability is not a good indicator of specific gravity and air-void content.

4.3 Recommendation

It is recommended that the reasons why the Butte 191 RHMA-G surface had much greater permeability should be explored further, including checking to determine whether it met construction compaction quality specifications. Additional RHMA-G projects should be tested to see if the Butte 191 project was an anomaly.

REFERENCES

1. California Highway Design Manual, Section 600.
2. Ongel, A., J. Harvey, E. Kohler, Q. Lu, B. Steven, and C. Monismith. 2008. **Summary Report: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results.** UCPRC-SR-2008-01. University of California Pavement Research Center, Davis and Berkeley, California.

APPENDIXES

Appendix A: Field Data

Field data from seven locations are shown in Tables A1 through A7.

A1. Field Data from Placer 174—PM 1.7/2.7

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
Pla174	RHMA-G	0	W1	RWP	U 6.9	4.3 R	64	62.5	73.13	12		3.00E-5
Pla174	RHMA-G	0	W1	BWP	U 6.9	4.3 R	66	56	78.08	11	Used Tier 4	1.95E-4
Pla174	RHMA-G	200	W1	RWP	U 6.1	4.3 L	63	61	79.12	11		3.78E-5
Pla174	RHMA-G	200	W1	BWP	U 6.1	4.3 L	49	41	74.45	11	Used Tier 4	2.22E-4
Pla174	RHMA-G	400	W1	RWP	U 8.7	0.9 R	64	46	63.05	11		4.85E-4
Pla174	RHMA-G	400	W1	BWP	U 8.7	0.9 R	63	38	64.18	11		7.30E-4
Pla174	RHMA-G	600	W1	RWP	U 9.0	0.7 L	64.5	63	100.34	11		2.17E-5
Pla174	RHMA-G	600	W1	BWP	U 9.0	0.7 L	64.5	61	64.39	11		8.03E-5
Pla174	RHMA-G	800	W1	RWP	U 1.8	7.1 R	64	62	83.15	13		3.54E-5
Pla174	RHMA-G	800	W1	BWP	U 1.8	7.1 R	63	37	66.73	13		7.39E-4
Pla174	RHMA-G	700	E1	RWP	D 7.6	3.2 R	65	61	74.28	11		7.92E-5
Pla174	RHMA-G	700	E1	BWP	D 7.6	3.2 R	65.5	65.4	80.17	11		1.77E-6
Pla174	RHMA-G	500	E1	RWP	D 7.9	7.6 R	64	57	69.44	12		1.55E-4
Pla174	RHMA-G	500	E1	BWP	D 7.9	7.6 R	62	54	69.19	12		1.85E-4
Pla174	RHMA-G	300	E1	RWP	D 5.8	2.9 L	65.5	65	135.86	12		5.23E-6
Pla174	RHMA-G	300	E1	BWP	D 5.8	2.9 L	64.5	61	76.68	12		6.74E-5
Pla174	RHMA-G	100	E1	RWP	D 4.8	0.1 L	64.5	63	93.57	13		2.33E-5
Pla174	RHMA-G	100	E1	BWP	D 4.8	0.1 L	60	53.5	76.45	13		1.39E-4
Pla174	RHMA-G	100	E1	RWP	D 3.1	2.6 R	65.5	60	63.91	11		1.27E-4
Pla174	RHMA-G	100	E1	BWP	D 3.1	2.6 R	64	61	75.49	11		5.89E-5
Pla174	RHMA-G	500	E1	RWP	D 9.1	5.5 R	65	64.6	130.97	12		4.37E-6
Pla174	RHMA-G	300	E1	BWP	D 9.1	5.5 R	64	60.5	74.6	12		6.98E-5
Pla174	RHMA-G	500	E1	RWP	D 7.7	5.4 R	65	64	88.35	12		1.63E-5
Pla174	RHMA-G	500	E1	BWP	D 7.7	5.4 R	62	59.5	84.91	12		4.49E-5
Pla174	RHMA-G	600	W1	RWP	U 5.9	0.6 L	63	61.5	109.16	12		2.05E-5
Pla174	RHMA-G	600	W1	BWP	U 5.9	0.6 L	63	60.5	68.81	12		5.45E-5
Pla174	RHMA-G	400	W1	RWP	U 7.6	0.3 R	63.5	62.5	86.16	14		1.71E-5
Pla174	RHMA-G	400	W1	BWP	U 7.6	0.3 R	63	44	65.63	14		5.07E-4
Pla174	RHMA-G	200	W1	RWP	U 6.9	5.7 R	66	65	69.6	12		2.03E-5
Pla174	RHMA-G	200	W1	BWP	U 6.9	5.7 R	62.5	61.5	103.47	12		1.44E-5

* RWP = right wheelpath, BWP = between wheelpaths

A2. Field Data from Butte 191—PM 6.5/7.5

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
But191	RHMA-G	0	S1	RWP	D 6.7	3.2 R	17	9.5	69.37	12		8.39E-3
But191	RHMA-G	0	S1	BWP	D 6.7	3.2 R	16	4.5	63.12	12		2.01E-2
But191	RHMA-G	200	S1	RWP	D 6.3	1.2 R	16	4	63.71	11		2.18E-2
But191	RHMA-G	200	S1	BWP	D 6.3	1.2 R	16	2	69.06	11		3.01E-2
But191	RHMA-G	400	S1	RWP	D 5.0	2.9 L	16	5	63.78	12		1.82E-2
But191	RHMA-G	400	S1	BWP	D 5.0	2.9 L	16	5	66.57	12		1.75E-2
But191	RHMA-G	600	S1	RWP	D 5.9	1.1 R	33	19	70.25	12	T3	1.80E-3
But191	RHMA-G	600	S1	BWP	D 5.9	1.1 R	16	10	70.44	12		6.67E-3
But191	RHMA-G	800	S1	RWP	D 8.5	7.7 L	33	29	83.56	13	T3	3.54E-4
But191	RHMA-G	800	S1	BWP	D 8.5	7.7 L	33	28	81.41	13	T3	4.62E-4
But191	RHMA-G	1000	S1	RWP	D 7.4	9.6 R	33	25	70.54	13	T3	9.00E-4
But191	RHMA-G	1000	S1	BWP	D 7.4	9.6 R	33	22	71.88	13	T3	1.29E-3
But191	RHMA-G	1200	S1	RWP	D 5.8	1.0 R	17	12	76.35	13		4.56E-3
But191	RHMA-G	1200	S1	BWP	D 5.8	1.0 R	33	19	63.46	13	T3	1.99E-3
But191	RHMA-G	1400	S1	RWP	D 6.7	0.6 R	16	13	74.19	13		2.80E-3
But191	RHMA-G	1400	S1	BWP	D 6.7	0.6 R	17	14	77.35	13		2.51E-3
But191	RHMA-G	1500	N1	RWP	U 7.1	1.6 R	33	22	70.38	13	T3	1.32E-3
But191	RHMA-G	1500	N1	BWP	U 7.1	1.6 R	16	12	71.5	13		4.02E-3
But191	RHMA-G	1300	N1	RWP	U 5.8	2.1 R	33	31	78.9	14		1.81E-4
But191	RHMA-G	1300	N1	BWP	U 5.8	2.1 R	16	13.5	74.5	14		2.28E-3
But191	RHMA-G	1100	N1	RWP	U 6.7	0.9 R	16	11	75.37	14		4.97E-3
But191	RHMA-G	1100	N1	BWP	U 6.7	0.9 R	33	27	74.75	14		6.14E-4
But191	RHMA-G	900	N1	RWP	U 8.5	6.7 L	33	31	76.63	15		1.87E-4
But191	RHMA-G	900	N1	BWP	U 8.5	6.7 L	33	31.5	70.25	15		1.51E-4
But191	RHMA-G	700	N1	RWP	U 5.7	10.3 R	33	29	73.09	15		4.04E-4
But191	RHMA-G	700	N1	BWP	U 5.7	10.3 R	33	28.5	68.75	15		4.88E-4
But191	RHMA-G	500	N1	RWP	U 4.9	1.1 L	33	18	60.66	14		2.29E-3
But191	RHMA-G	500	N1	BWP	U 4.9	1.1 L	33	26	63.5	14		8.59E-4
But191	RHMA-G	300	N1	RWP	U 5.1	0.3 R	16	6	70.06	14		1.40E-2
But191	RHMA-G	300	N1	BWP	U 5.1	0.3 R	16	9	65.03	14		8.85E-3
But191	RHMA-G	100	N1	RWP	U 6.2	0.2 L	16	3	47.1	14		3.55E-2
But191	RHMA-G	100	N1	BWP	U 6.2	0.2 L	16	3	63.22	14		2.65E-2

* RWP = right wheelpath, BWP = between wheelpaths

A3. Field Data from Sacramento 160—PM 6.0/7.0

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
Sac160	RHMA-G	0	E1	BWP	U 0.9	4.3 R	33	33	88.75	8		0.00E+0
Sac160	RHMA-G	0	E1	RWP	U 0.9	4.3 R	32	18	36.22	8	leak	3.63E-3
Sac160	RHMA-G	200	E1	BWP	U 0.1	2.3 R	33	19	63.03	7		2.00E-3
Sac160	RHMA-G	200	E1	RWP	U 0.1	2.3 R	64	35.5	62.62	7		8.72E-4
Sac160	RHMA-G	400	E1	BWP	D 0.2	2.1 R	64.5	63	80.41	8		2.71E-5
Sac160	RHMA-G	400	E1	RWP	D 0.2	2.1 R	64.5	64	71	8		1.02E-5
Sac160	RHMA-G	600	E1	BWP	D 0.3	4.2 R	33	23	74.2	11		1.11E-3
Sac160	RHMA-G	600	E1	RWP	D 0.3	4.2 R	64	56	73	11		1.69E-4
Sac160	RHMA-G	800	E1	BWP	D 0.3	7.8 R	64	41	64.03	13		6.44E-4
Sac160	RHMA-G	800	E1	RWP	D 0.3	7.8 R	64	58	67.13	13		1.36E-4
Sac160	RHMA-G	1000	E1	BWP	U 0.7	2.7 R	64	63.5	79.97	13		9.09E-6
Sac160	RHMA-G	1000	E1	RWP	U 0.7	2.7 R	64	64	71.19	13		0.00E+0
Sac160	RHMA-G	1200	E1	BWP	D 0.5	2.1 R	65	61	68.88	6		8.54E-5
Sac160	RHMA-G	1200	E1	RWP	D 0.5	2.1 R	64.5	64.5	65.87	6		0.00E+0
Sac160	RHMA-G	1400	E1	BWP	U 0.5	0.9 R	16	10	62.85	8		7.48E-3
Sac160	RHMA-G	1400	E1	RWP	U 0.5	0.9 R	62	38	64.88	8		6.99E-4
Sac160	RHMA-G	1300	W1	BWP	D 0.3	3.6 R	65	40	64.84	7		6.94E-4
Sac160	RHMA-G	1300	W1	RWP	D 0.3	3.6 R	63.5	62.5	72.63	7		2.02E-5
Sac160	RHMA-G	1100	W1	BWP	U 0.2	1.8 L	64	53	66.28	7		2.64E-4
Sac160	RHMA-G	1100	W1	RWP	U 0.2	1.8 L	65	64	71.34	7		2.01E-5
Sac160	RHMA-G	900	W1	BWP	U 0.4	4.0 R	64.5	64	65.69	8		1.10E-5
Sac160	RHMA-G	900	W1	RWP	U 0.4	4.0 R	64.5	63	72.78	8		3.00E-5
Sac160	RHMA-G	700	W1	BWP	D 0.2	1.4 R	64	54	64.31	8		2.45E-4
Sac160	RHMA-G	700	W1	RWP	D 0.2	1.4 R	33	19	66	8		1.91E-3
Sac160	RHMA-G	500	W1	BWP	D 0.3	2.2 R	65	56	67.5	8		2.05E-4
Sac160	RHMA-G	500	W1	RWP	D 0.3	2.2 R	65	51	61.97	8		3.63E-4
Sac160	RHMA-G	300	W1	BWP	D 0.5	3.8 R	65	59	67.59	9		1.33E-4
Sac160	RHMA-G	300	W1	RWP	D 0.5	3.8 R	65	64	65.91	9		2.18E-5
Sac160	RHMA-G	100	W1	BWP	D 0.2	4.0 R	65	62.5	75.1	8		4.84E-5
Sac160	RHMA-G	100	W1	RWP	D 0.2	4.0 R	64	61	72.44	8		6.14E-5

* RWP = right wheelpath, BWP = between wheelpaths

A4. Field Data from Yuba 20—PM R1.6/R2.0

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
Yub20	HMA	375	W1	RWP	D 1.3	2.9 R	63	48	66.44	10		3.79E-4
Yub20	HMA	375	W1	BWP	D 1.3	2.9 R	65	61	66.97	10		8.79E-5
Yub20	HMA	300	W1	RWP	U 0.8	2.8 R	66	65.5	67.72	9		1.04E-5
Yub20	HMA	300	W1	BWP	U 0.8	2.8 R	33	18	55.5	9	leak	2.50E-3
Yub20	HMA	225	W1	RWP	D 0.3	3.4 R	66	66	67.56	8		0.00E+0
Yub20	HMA	225	W1	BWP	D 0.3	3.4 R	63.5	57	76.13	8		1.31E-4
Yub20	HMA	150	W1	RWP	0	1.4 R	64	64	64.56	7		0.00E+0
Yub20	HMA	150	W1	BWP	0	1.4 R	62.5	60.5	63.39	7		4.75E-5
Yub20	HMA	75	W1	RWP	U 0.9	0.9 R	66	64.5	77.41	6		2.75E-5
Yub20	HMA	75	W1	BWP	U 0.9	0.9 R	63.5	63.5	68	6		0.00E+0
Yub20	HMA	75	E2	RWP	D 0.1	5.8 R	64	63.5	90	6		8.07E-6
Yub20	HMA	75	E2	BWP	D 0.1	5.8 R	64.5	64.5	70.29	6		0.00E+0
Yub20	HMA	75	E1	RWP	D 0.5	4.8 R	64	55	59.31	6	leak	2.37E-4
Yub20	HMA	75	E1	BWP	D 0.5	4.8 R	66	66	70.88	6		0.00E+0
Yub20	HMA	150	E1	RWP	U 0.1	2.9 R	63	63	60.44	8		0.00E+0
Yub20	HMA	150	E1	BWP	U 0.1	2.9 R	64.5	63.5	63.9	8		2.27E-5
Yub20	HMA	225	E1	RWP	D 0.3	4.1 R	66	66	60.6	8		0.00E+0
Yub20	HMA	225	E1	BWP	D 0.3	4.1 R	66	63	64.22	8		6.71E-5
Yub20	HMA	300	E1	RWP	U 0.1	3.4 R	66	66	61.53	7		0.00E+0
Yub20	HMA	300	E1	BWP	U 0.1	3.4 R	64	64	61.53	7		0.00E+0
Yub20	HMA	375	E1	RWP	U 0.7	0.1 L	33	19	36.03	7	leak	3.50E-3
Yub20	HMA	375	E1	BWP	U 0.7	0.1 L	65	63	74.59	7		3.88E-5

* RWP = right wheelpath, BWP = between wheelpaths

A5. Field Data from Santa Clara 152—PM 19.9/20.9

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
SCl152	HMA	0	E2	RWP	U 2.24	3.7 R	65.5	59.5	63.09	11		1.41E-4
SCl152	HMA	0	E2	BWP	U 2.24	3.7 R	66	59	66.07	11		1.57E-4
SCl152	HMA	2	E2	RWP	U 2.24	5.3 R	64.5	63	69.7	10		3.13E-5
SCl152	HMA	2	E2	BWP	U 2.24	5.3 R	64.5	61.5	69.81	10		6.32E-5
SCl152	HMA	4	E2	RWP	U 5.34	3.9 R	64.5	64.5	63.43	8		0.00E+0
SCl152	HMA	4	E2	BWP	U 5.34	3.9 R	63	59	67.32	8		9.03E-5
SCl152	HMA	6	E2	RWP	U 5.54	3.0 R	64	63	70.78	9		2.06E-5
SCl152	HMA	6	E2	BWP	U 5.54	3.0 R	65	56.5	67.16	9		1.93E-4
SCl152	HMA	8	E2	RWP	U 5.94	2.4 R	64.5	63.5	69.12	11		2.09E-5
SCl152	HMA	8	E2	BWP	U 5.94	2.4 R	62	57	65.91	11		1.18E-4
SCl152	HMA	10	E2	RWP	U 5.84	2.2 R	62.5	62	91.39	9		8.14E-6
SCl152	HMA	10	E2	BWP	U 5.84	2.2 R	64	61.5	62.75	9		5.88E-5
SCl152	HMA	12	E2	RWP	U 3.94	2.7 L	64	62	73.04	11		4.03E-5
SCl152	HMA	12	E2	BWP	U 3.94	2.7 L	62.5	59.5	66.12	11		6.89E-5
SCl152	HMA	14	E2	RWP	U 3.34	3.5 L	65.5	65.5	62.96	11		0.00E+0
SCl152	HMA	14	E2	BWP	U 3.34	3.5 L	64	61	71.97	11		6.18E-5
SCl152	HMA	16	E2	RWP	U 3.94	5.7 L	66	65.25	70	14		1.51E-5
SCl152	HMA	16	E2	BWP	U 3.94	5.7 L	64.5	64	64.32	14		1.12E-5
SCl152	HMA	18	E2	RWP	U 2.74	8.0 L	64.5	62.5	66.88	14		4.36E-5
SCl152	HMA	18	E2	BWP	U 2.74	8.0 L	62.5	62.5	57	14		0.00E+0

* RWP = right wheelpath, BWP = between wheelpaths

A6. Field Data from Solano 680—PM 6.0/7.0

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
Sol680	HMA	0	N2	BWP	D 0.7	4.7 L	65	56	64.25	12		2.15E-4
Sol680	HMA	0	N2	RWP	D 0.7	4.7 L	65	39	63.81	12		7.42E-4
Sol680	HMA	1	N2	BWP	D 0.4	4.6 L	65	59	67.03	13		1.34E-4
Sol680	HMA	1	N2	RWP	D 0.4	4.6 L	33	22	62.78	13	Leak	1.48E-3
Sol680	HMA	2	N2	BWP	D 1.5	1.5 L	62.5	58.5	64.87	13		9.45E-5
Sol680	HMA	2	N2	RWP	D 1.5	1.5 L	63.5	48	62.22	13		4.17E-4
Sol680	HMA	3	N2	BWP	D 0.3	2.5 R	33	18.5	61	13		2.17E-3
Sol680	HMA	3	N2	RWP	D 0.3	2.5 R	33	22	60.91	13		1.52E-3
Sol680	HMA	4	N2	BWP	0	2.7 R	65	38	64.44	13		7.72E-4
Sol680	HMA	4	N2	RWP	0	2.7 R	66	48	61.56	13		4.79E-4
Sol680	HMA	5	N2	BWP	U 0.1	3.4 R	66	51	63.88	13		3.74E-4
Sol680	HMA	5	N2	RWP	U 0.1	3.4 R	45	43	64	13		6.58E-5
Sol680	HMA	6	N2	BWP	0	3.9 R	66	51	63.51	13		3.76E-4
Sol680	HMA	6	N2	RWP	0	3.9 R	66	48	63.03	13		4.68E-4
Sol680	HMA	7	N2	BWP	0	4.1 R	65	53	59.01	13		3.20E-4
Sol680	HMA	7	N2	RWP	0	4.1 R	33	23	60.25	13		1.37E-3
Sol680	HMA	8	N2	BWP	U 0.4	3.9 R	64.5	59	62.6	13		1.32E-4
Sol680	HMA	8	N2	RWP	U 0.4	3.9 R	65	50	63.06	13		3.85E-4
Sol680	HMA	0	S2	BWP	U 0.2	4.7 R	65	48	62.03	15		4.53E-4
Sol680	HMA	0	S2	RWP	U 0.2	4.7 R	64.5	47	63.97	15		4.58E-4
Sol680	HMA	1	S2	BWP	0	4.0 R	65	60.5	64.9	12		1.02E-4
Sol680	HMA	1	S2	RWP	0	4.0 R	65.5	60	62.87	12		1.29E-4
Sol680	HMA	2	S2	BWP	D 0.5	4.2 R	65.5	60.5	65.24	13		1.13E-4
Sol680	HMA	2	S2	RWP	D 0.5	4.2 R	65	39	61	13		7.76E-4
Sol680	HMA	3	S2	BWP	D 0.4	4.6 R	66	59	62.28	12		1.67E-4
Sol680	HMA	3	S2	RWP	D 0.4	4.6 R	64	50	62.97	12		3.63E-4
Sol680	HMA	4	S2	BWP	D 0.7	2.7 R	65	46	61.41	12		5.22E-4
Sol680	HMA	4	S2	RWP	D 0.7	2.7 R	65	50	62.44	12		3.89E-4
Sol680	HMA	5	S2	BWP	D 0.4	2.4 R	65	49	60.25	12		4.34E-4
Sol680	HMA	5	S2	RWP	D 0.4	2.4 R	65	44	81.07	12		4.46E-4
Sol680	HMA	6	S2	BWP	D 0.7	1.8 R	66	61.5	62.43	13		1.05E-4
Sol680	HMA	6	S2	RWP	D 0.7	1.8 R	66	58	65.53	13		1.83E-4
Sol680	HMA	7	S2	BWP	D 0.3	3.9 L	66	55.5	62.12	13		2.58E-4
Sol680	HMA	7	S2	RWP	D 0.3	3.9 L	66	59.5	63.97	13		1.50E-4
Sol680	HMA	8	S2	BWP	D 0.2	3.2 L	66	49	64.47	13		4.28E-4
Sol680	HMA	8	S2	RWP	D 0.2	3.2 L	66	53	67.22	13		3.02E-4

* RWP = right wheelpath, BWP = between wheelpaths

A7. Field Data from Mono 120—PM 43.5/44.0

Site	Surface Material	Postmile/ Station	Lane Number	Transverse Position*	Profile Slope (%)	Transverse Slope (%)	Initial Head (cm)	Final Head (cm)	Elapsed Time (sec)	Water Temp	Notes	Permeability (cm/sec)
Mon120	HMA	0	W1	RWP	1.24	1.7 R	65	35	59.41	16		9.65E-4
Mon120	HMA	0	W1	BWP	1.24	1.7 R	33	19	64.88	16		1.95E-3
Mon120	HMA	0	E1	RWP	D 1.0	1.9 R	65	48	66.88	16		4.20E-4
Mon120	HMA	0	E1	BWP	D 1.0	1.9 R	33	22	68.84	16		1.35E-3
Mon120	HMA	1	W1	RWP	U 1.0	2.0 R	65	48.5	63.97	16	grinding	4.24E-4
Mon120	HMA	1	W1	BWP	U 1.0	2.0 R	65	36	58.75	16	grinding	9.32E-4
Mon120	HMA	1	E1	RWP	D 1.4	0.9 R	65.5	53.5	61.88	16	grinding	3.03E-4
Mon120	HMA	1	E1	BWP	D 1.4	0.9 R	33	26	67	16	grinding	8.14E-4
Mon120	HMA	2	W1	RWP	D 0.5	1.7 R	33	23	62.53	14	grinding	1.32E-3
Mon120	HMA	2	W1	BWP	D 0.5	1.7 R	17	14	73.37	14	grinding	2.65E-3
Mon120	HMA	2	E1	RWP	U 0.2	1.0 R	66	63.5	65.98	14	grinding	5.42E-5
Mon120	HMA	2	E1	BWP	U 0.2	1.0 R	65	39	62.5	14	grinding	7.57E-4
Mon120	HMA	3	W1	RWP	U 0.9	2.1 R	33	21	68.66	12		1.51E-3
Mon120	HMA	3	W1	BWP	U 0.9	2.1 R	17	13.5	66.75	12		3.45E-3
Mon120	HMA	3	E1	RWP	D 0.9	0.7 R	65	51	61.63	12		3.65E-4
Mon120	HMA	3	E1	BWP	D 0.9	0.7 R	65	38	64.69	12		7.69E-4
Mon120	HMA	4	W1	RWP	0	1.8 R	33	19	68.07	13		1.86E-3
Mon120	HMA	4	W1	BWP	0	1.8 R	17	13	63.87	13		4.20E-3
Mon120	HMA	4	E1	RWP	D 0.2	0.4 L	65.5	47	66.06	13		4.65E-4
Mon120	HMA	4	E1	BWP	D 0.2	0.4 L	33	25	66.28	13		9.58E-4
Mon120	HMA	5	W1	RWP	0	1.9 R	33	23	67.54	12		1.22E-3
Mon120	HMA	5	W1	BWP	0	1.9 R	17	14	64.37	12		3.02E-3
Mon120	HMA	5	E1	RWP	U 0.2	1.4 L	33	23	68.5	12		1.21E-3
Mon120	HMA	5	E1	BWP	U 0.2	1.4 L	33	24	56.44	12		1.29E-3
Mon120	HMA	6	W1	RWP	D 0.6	1.8 R	66	54	65.31	12		2.85E-4
Mon120	HMA	6	W1	BWP	D 0.6	1.8 R	33	22	66.6	12		1.39E-3
Mon120	HMA	6	E1	RWP	U 0.3	0.4 R	33	21	67.5	12		1.53E-3
Mon120	HMA	6	E1	BWP	U 0.3	0.4 R	16	13	67.93	12		3.06E-3
Mon120	HMA	7	W1	RWP	D 0.7	2.2 R	66	38	63.53	13	grinding	8.05E-4
Mon120	HMA	7	W1	BWP	D 0.7	2.2 R	33	24.5	70.44	13	grinding	9.67E-4
Mon120	HMA	7	E1	RWP	U 0.4	0.2 R	66	57.5	65.81	13		1.94E-4
Mon120	HMA	7	E1	BWP	U 0.4	0.2 R	33	23	63.54	13		1.30E-3

* RWP = right wheelpath, BWP = between wheelpaths

Appendix B: Statistical Tests

Statistical tests were conducted at the 95% confidence interval to determine whether the means are equal, from different directions and different wheelpaths, from individual locations in Table B1 and from the complete data set in Table B2.

B1. Statistical t-tests assuming unequal variances from individual locations. Bolded values show t-stat values greater than the two-tail t-critical value, indicating a difference in means.

Location	Statistical Test Characteristics	Direction Comparison		Wheelpath Comparison	
		NB or EB	SB or EB	BWP	RWP
Placer 174	Mean	6.98E-5	0.000201	0.000207	7.19E-5
	Variance	3.65E-9	6.86E-8	6.12E-8	1.5E-8
	Observations	14	16	15	15
	Degrees of freedom	17		20	
	t Stat	-1.93967		1.898798	
	P(T<=t) two-tail	0.069197		0.072115	
	t Critical two-tail	2.109816		2.085963	
Butte 191	Mean	0.006414	0.008713	0.007772	0.007355
	Variance	0.000109	9.11E-5	0.000101	0.000102
	Observations	16	16	16	16
	Degrees of freedom	30		30	
	t Stat	-0.64981		0.11693	
	P(T<=t) two-tail	0.520761		0.907695	
	t Critical two-tail	2.042272		2.042272	
Sacramento 160	Mean	0.001055	0.000288	0.000864	0.00053
	Variance	3.89E-6	2.55E-7	3.65E-6	1.01E-6
	Observations	16	14	15	15
	Degrees of freedom	17		21	
	t Stat	1.501728		0.599582	
	P(T<=t) two-tail	0.151514		0.555199	
	t Critical two-tail	2.109816		2.079614	
Yuba 20	Mean	0.000323	0.000318	0.000263	0.000379
	Variance	1.01E-6	6.0E-7	5.51E-7	1.09E-6
	Observations	12	10	11	11
	Degrees of freedom	20		18	
	t Stat	0.013125		-0.29959	
	P(T<=t) two-tail	0.989658		0.767925	
	t Critical two-tail	2.085963		2.100922	
Santa Clara 152	Mean			8.229E-5	3.211E-5
	Variance			3.625E-9	1.695E-9
	Observations			10	10
	Degrees of freedom			16	
	t Stat			**2.1757606**	
	P(T<=t) two-tail			0.0449048	
	t Critical two-tail			2.1199053	
Solano 680	Mean	0.00064	0.000321	0.000398	0.000562
	Variance	3.60E-7	3.42E-8	2.30E-7	2.04E-7
	Observations	18	18	18	18
	Degrees of freedom	20		34	
	t Stat	**2.153745**		-1.05778	
	P(T<=t) two-tail	0.043638		0.297615	
	t Critical two-tail	2.085963		2.032245	
Mono 120	Mean	0.00093	0.001684	0.001803	0.000808
	Variance	5.31E-7	1.242E-6	1.23E-6	3.21E-7
	Observations	16	16	16	16
	Degrees of freedom	26		22	
	t Stat	**-2.272576**		**3.196902**	
	P(T<=t) two-tail	0.03156		0.004162	
	t Critical two-tail	2.05553		2.073873	

Bolded values show t-stat values greater than the two-tail t-critical value, indicating a difference in means.

B2. Statistical t-tests assuming unequal variances from the complete dataset

Surface Material	Statistical Test Characteristics	Direction Comparison		Wheelpath Comparison	
		NB or EB	SB or EB	BWP	RWP
RHMA-G	Mean	2.62E-3	3.19E-3	3.05E-3	2.75E-3
	Variance	4.56E-5	4.71E-5	4.69E-5	4.60E-5
	Observations	46	46	46	46
	Degrees of freedom	90		90	
	t Stat	-0.40035		0.20962	
	P(T<=t) two-tail	0.68985		0.83444	
	t Critical two-tail	1.98667		1.98667	
HMA	Mean	4.19E-4	3.88E-4	7.22E-4	5.01E-4
	Variance	5.64E-7	2.46E-7	1.02E-6	4.28E-7
	Observations	54	32	55	55
	Degrees of freedom	83		93	
	t Stat	0.23048		1.36838	
	P(T<=t) two-tail	0.81828		0.17449	
	t Critical two-tail	1.98896		1.98580	
HMA, excluding Mono 120	Mean			4.09E-4	4.05E-4
	Variance			4.72E-7	4.22E-7
	Observations			43	43
	Degrees of freedom			84	
	t Stat			0.02812	
	P(T<=t) two-tail			0.97763	
	t Critical two-tail			1.98861	

t-Stat values less than the two-tail t-Critical value indicate no statistical difference in the means.

B3. Statistical t-tests assuming unequal variances comparing the RHMA-G data to the HMA data with and without the Mono 120 data set

Statistical Test Characteristics	HMA	RHMA-G	HMA, excluding Mono 120	RHMA-G
Mean	6.12E-4	2.90E-3	3.27E-4	2.90E-3
Variance	7.28E-7	4.60E-5	3.44E-7	4.60E-5
Observations	110	92	78	92
Degrees of freedom	93		93	
t Stat	-3.22183		-3.62984	
P(T<=t) two-tail	0.00176		0.00046	
t Critical two-tail	1.98580		1.98580	

t-Stat values greater than the two-tail t-Critical value indicate a statistical difference in the means.

B4. Statistical t-tests assuming unequal variances comparing the HMA data to the RHMA-G data with and without the Butte 191 data set.

Statistical Test Characteristics	**HMA**	**RHMA-G, excluding Butte 191**	**HMA, excluding Mono 120**	**RHMA-G, excluding Butte 191**
Mean	6.12E-4	4.18E-4	3.27E-4	4.18E-4
Variance	7.28E-7	1.22E-6	3.44E-7	1.22E-6
Observations	110	60	78	60
Degrees of freedom	98		84	
t Stat	1.17791		-0.58115	
P(T<=t) two-tail	0.24169		0.56270	
t Critical two-tail	1.98447		1.98861	

t-Stat values less than the two-tail t-Critical value indicate no statistical difference in the means.

Appendix C: Analysis of Mono 120 Dataset

C1. Linear regression using all ten data points

Regression Statistics	
Multiple R	0.46197
R Square	0.21342
Standard Error	0.06016
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.007855	0.007855	2.170558	0.179
Residual	8	0.028951	0.003619		
Total	9	0.036806			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.01546	0.023561	85.54377	3.89E-13	1.961	2.0698
Permeability	244.127	165.7028	1.473282	0.178898	-138	626.24

C2. Linear regression using eight data points, excluding Core 1-4 and Core 2-8.

Regression Statistics	
Multiple R	0.94370
R Square	0.89058
Standard Error	0.02273
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.025232	0.025232	48.8332	0.00043
Residual	6	0.003100	0.0005167		
Total	7	0.028332			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.9789	0.0110809	178.58872	2.1E-12	1.9518	2.0060
Permeability	1714.67	245.37118	6.9880751	0.00043	1114.27	2315.07

C3. Linear regression using eight data points, excluding cores from Location 1 and Location 2. Results are very similar to results that exclude Core 1-4 and Core 2-8.

Regression Statistics	
Multiple R	0.92255
R Square	0.8511
Standard Error	0.02472
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.013977	0.013977	22.86373	0.008765
Residual	4	0.002445	0.000611		
Total	5	0.016422			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.9773	0.013051	151.5006	1.14E-8	1.9411	2.0135
Permeability	1585.93	331.6728	4.781604	0.008765	665.06	2506.80